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Scientific production of renewable energies worldwide: An overview

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ABSTRACT

This paper reviews the scientific production of renewable energies, namely, solar, wind, biomass, hydropower and geothermal, from 1979 to 2009. The production of all the countries in the world is analysed, paying particular attention to renewable energies and research institutions. The production of scientific research for each type of energy is represented on world maps to show the degree of relationship between this research and the resources of these energies. It is observed that biomass is the most studied, both by number of publications, with 56% of the publications on renewable energy, and by geographical distribution. The next in importance by number of publications is solar energy (26%). The countries investigating solar energy, however, are not necessarily those with the greatest availability of this resource. Wind is the third positioned in publication (11%). Wind is being investigated by countries that most have implemented this type of energy production. Hydro and geothermal energies are also investigated by countries with great abundance of this resource. It is observed that research on renewable energy is highly concentrated in a few countries (12 or 14, depending on the energy type), accounting for between 70 and 80% of scientific production. The role of the USA as a leader in research in all renewable energies studies is emphasised. NASA is the leading institution for solar and wind energy, the Chinese Academy of Sciences leads in hydropower and biomass, and the U.S. Geological Survey leads in geothermal energy.

Contents

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1. Introduction

The processes of industrialisation and economic development require energy [1]. The demand for energy is expected to increase at a faster rate in upcoming years [2,3], partly due to the exponential growth of the world's population [4]. Energy resources have been divided into three categories: fossil fuels, renewable resources and nuclear resources [5]. Nuclear energy can cause serious problems for the environment [6–8] and human health [9,10]; for example, those caused by nuclear accidents such as Chernobyl in 1986.

Combustible fuels are the world's main energy resource and are at the centre of global energy demands [11]. However, the reserves of fossil fuels are limited, and their large-scale use is associated with environmental deterioration [12,13]. Known negative effects of using fossil fuels include [14] acid rain, ozone layer depletion and global climate change. The result has been a rapid growth in the level of greenhouse gas emissions and an increase in fuel prices [15], which are the main driving forces behind efforts to utilise renewable energy sources [16].

A renewable energy source (RES) can be defined as a simple sustainable resource available over the long term at a reasonable cost that can be used for any task without negative effects [17,18]. Other authors consider RESs as clean sources of energy and that the optimal use of these resources minimises environmental impacts, produces minimum secondary wastes and is sustainable based on current and future economic and social needs [19]. Positive points in the use of RESs are the increased diversity in energy supply options, both for developed and developing countries [17,20,21], less dependence on fossil fuels [18], the increase of net employment, the creation of export markets [21,22] and a reduction in greenhouse gas emissions and climate change [17,20,22–24].

RESs include biomass, hydropower, geothermal, solar, wind and marine energies [25]. Today, RESs supply 14% of the total world energy demand [19,26,27], and the share of RESs is expected to increase significantly (30–80% in 2100) [19].

One of the factors that can foster the development and use of RESs is research. The analysis of research efforts and trends can be accomplished by examining the number of indexed scientific journals [28–34]. The number of scientific publications on renewable energy has been evaluated for biomass in 1992 [29]. It has recently been evaluated using Scopus data base: for Europe during the period 2000 to 2007 [35], without differentiating the type of renewable energy or the research institutions most involved in the research of these energies; and worldwide during the period 2003 to 2008 [36], also without differentiating the type of renewable energy. The main conclusion of this work was that during this period, U.S., China, U.K., India, Turkey and Japan were the countries with the greatest scientific production and most cites, and China was the country with the greatest increase in production. For this reason, the aim of this work is to examine the research efforts, by differentiating the various fields of renewable energy researched by all countries in the world in the last 30 years (1979 to 2009) and the major research institutions, as well as to represent this information in world maps in order to show their geographical distribution.

The selection of these variables is justified due to the importance of studying, first, the evolution of the research of different renewable energy sources over the last 30 years. Second, we geolocate the renewable energy research, noting areas or countries that are making the greatest efforts and checking whether these efforts are devoted to the exploitation of these resources or not. Finally, we study the contribution of leading scientific institutions to each of the different energy sources, noting the main focuses of the same.

2. Methodology

A literature review on the status and progress of research in the main renewable energy sources worldwide for the period 1979–2009 was conducted, using the number of web publications in the ISI (ISI Web of Knowledge) as a reference, as has been done for other studies from different areas of knowledge [37–47]. The extensive literature search focuses on the main renewable energies: solar, wind, biomass, geothermal and hydropower, given their importance and proliferation in the last three decades. The country, year and institution of publication were included.

The methodology included the search for keywords in each of the publications, establishing a series of keywords for each of the renewable energy studies, and performing the logical union of the same order to avoid the appearance of duplicate publications in the study. The keywords used for each renewable energy were as follows: for solar: solar energy, solar thermal energy, solar power and photovoltaic; for wind energy: wind Energy, wind power and wind farm; for biomass: biomass, bioenergy, biogas and biofuel; for geothermal: geothermal energy, geothermal electricity, geothermal heating; and for hydropower: hydropower and hydroelectric.

3. Results

3.1. Global comparison between renewable energy sources.

According to the report of the International Energy Agency (IEA) of 2011 [48], electricity generation from renewable sources worldwide in 1990 was 19.5% and grew by an average of 2.7% per year, while the total electricity generation grew by 3% annually, and in 2008, the percentage of electricity produced from renewable sources was 18.5%. This decrease is mainly the result of the slow growth of the main source of renewable energy, hydropower, in the countries of the OECD (Organisation for Economic Co-operation and Development) [48].

In 2010, the contribution of different renewable energy sources to the overall energy production was estimated to be [49,50] 16.6% hydropower (large and small), 2.56% wind, 1.95% biomass, 0.67% geothermal, 0.13% solar (PV and Solar Thermal) and 0.01% marine.

Fig. 1 presents percentages of all scientific journals in the ISI database related to renewable energies during the period from 1979 to 2009. It is noted that in the last 30 years, more than half of the global research effort (56%) has been in related to the use of biomass as renewable energy, followed by solar energy, which was more than double (26%) of wind power (11%). These data draw attention to the relatively low (2%) focus on hydropower research, which, as seen, is the renewable energy that produces more energy. The explanation for this low percentage can be found in two factors: this source is limited to very specific areas of the planet with water resource availability (10 countries produce 69.8% of this energy) [51]; and hydropower technology is regarded as the most mature of all considered RESs [52].

Some of the technologies associated with biomass are still being developed as biomass gasification, and others in the state of deployment are co-fired biomass and direct-fired biomass [52]. Wind energy technologies are in a state of deployment, some at the beginning of this phase (offshore wind) and others at the end (onshore wind) [52]. Taking into account the evolution of this research effort (Fig. 2), we can consider Hydropower and Geothermal to have been stable over the last 30 years. Biomass, solar and wind power are less stable, following an exponential trend. There has been acceleration in the investigation of these three renewable energies since 1991, when they began to show significant

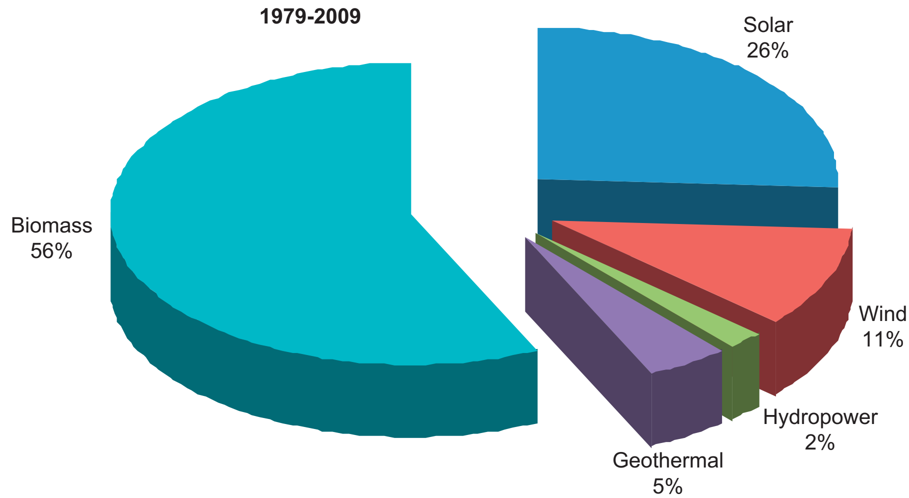


Fig. 1. Distribution of scientific publications (1979–2009) per renewable energy.

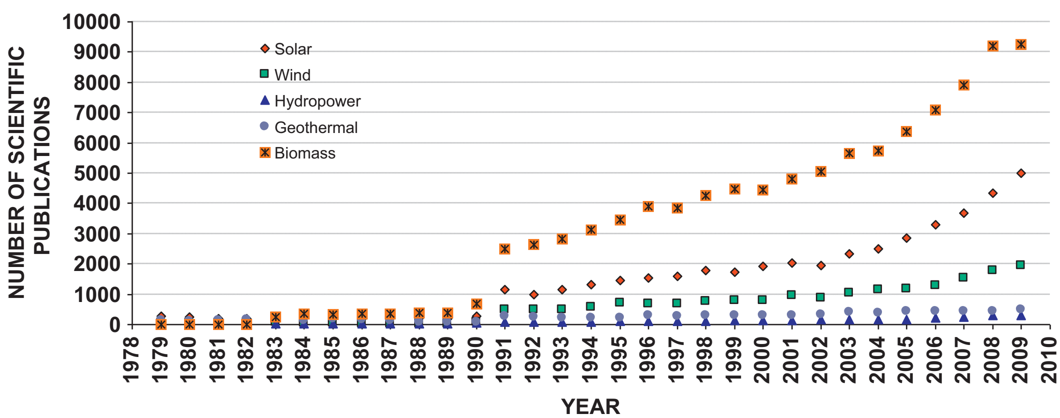


Fig. 2. Evolution of scientific publications (1979–2009) on renewable energies.

differences among the publications of the different renewable energies. The exponential trend in scientific publications in a given field has been observed in other studies [16,33].

3.2. Analysis of renewable energies per country.

3.2.1. Solar

Fig. 3 shows the number of scientific publications on solar energy in the period 1979–2009 in all countries. The following countries contributed the most scientific publications in this field: USA(24.4%), Japan (7.2%), Germany (7.1%), United Kingdom (6.1%), China (5.5%), France (4.7%), India (4%), Italy (3.6%), Russian Federation (3.2%), Spain (2.8%) Switzerland (2.2%), Canada (2.1%) and Australia (1.9%). These 13 countries, out of 233, contributed 75% of the scientific production related to solar energy, which means that this research is very concentrated.

It should be noted that the countries which conducted the most research in solar energy are not necessarily those with the most of this resource (except Australia) because, if we compare them with a map of the solar energy potential [53], it is observed that the areas with the highest mean potential solar per year in kW h m^{-2} are Africa and the Middle East, and these countries do not conduct solar energy research (see Fig. 3). Very conducive conditions are found in the Sahara, where the potential electricity production is more than 500 times the electricity consumption of the EU member states [53].

3.2.2. Wind

Fig. 4 shows the number of scientific publications on wind energy in the period 1979–2009 in all countries. The following countries contributed the most scientific publications in this field: USA (29.2%), United Kingdom (8.5%), Germany (6.7%), Japan (4.8%), France (4.5%), Canada (4.3%), Russian Federation (3.4%), China (3.2%), Italy (3%), Netherlands (2.4%), Australia (2.4%), India (2.1%), Spain (2%) and Sweden (2%). These 14 countries, out of 233, contributed 78.5% of the scientific production related to wind energy, which means that this research is highly concentrated, as was the case with solar energy. Some countries that have opted for wind energy research are leaders in MW installed as of 2009 [54]: USA (35,159 MW), Germany (26,010 MW), China (26,010 MW), India (10,925) and Spain (19,149 MW). This is possibly due to the favourable policy on renewable energy in these countries, as it is the case of Spain [55–59].

3.2.3. Hydropower

Hydroelectric power is currently the largest of the perpetual or so-called renewable energy resources (RESs). Hydropower contributes to electricity generation in 160 countries, but five of them (Brazil, Canada, China, Russia and the USA) account for more than half of the global hydropower production [60].

Fig. 5 shows the number of scientific publications in the period 1979–2009 in all countries on hydropower. The following

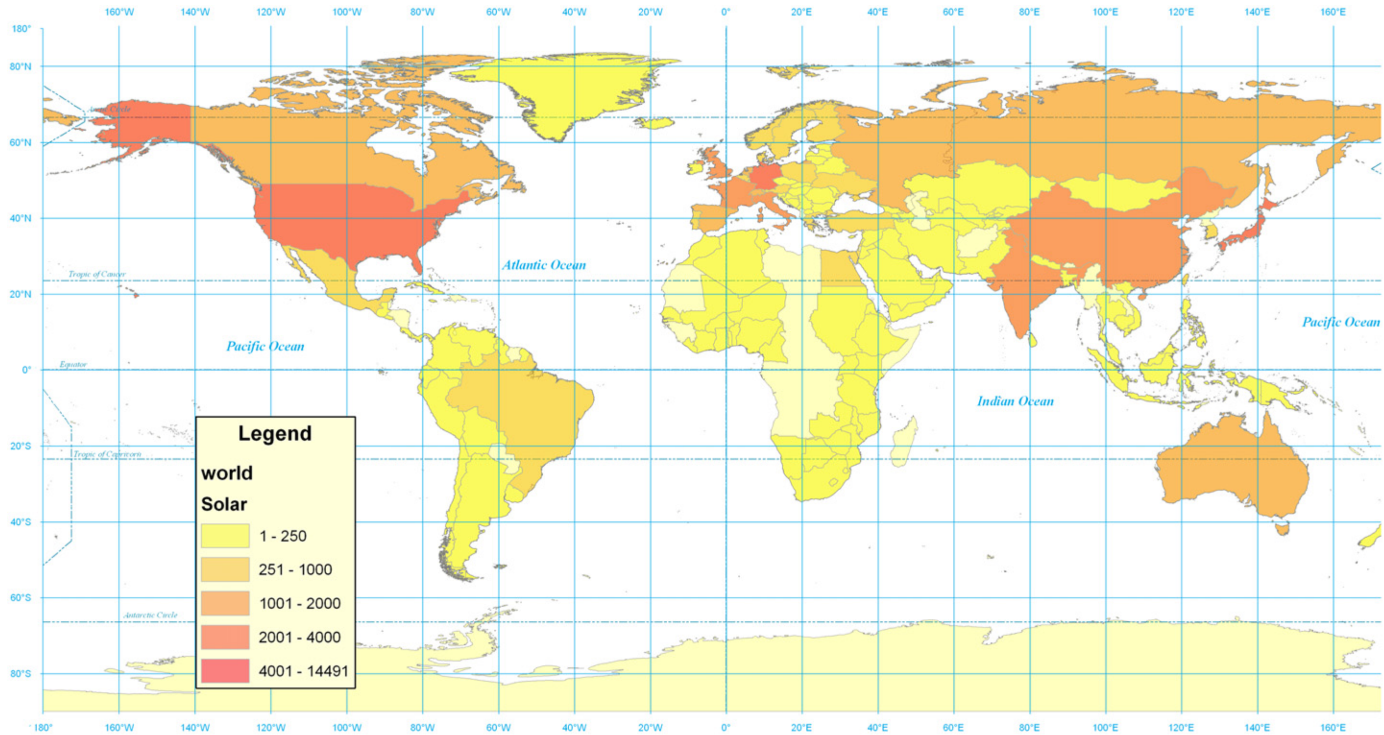


Fig. 3. World map of the number of scientific journals published on solar energy in the period 1979–2009.

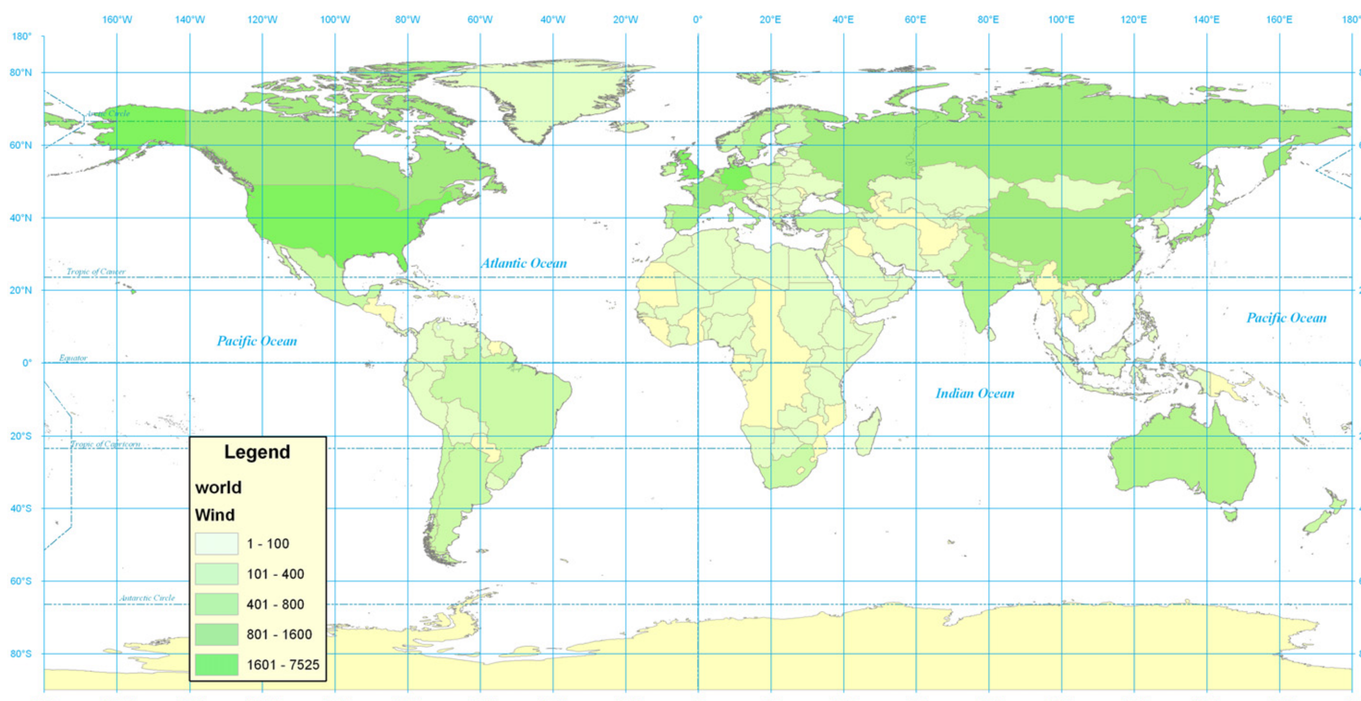


Fig. 4. World map of the number of scientific journals published on wind energy in the period 1979–2009.

countries have contributed the most scientific publications in this field: USA(20.4%), Canada (11%), Brazil (6.8%), China (5.9%), United Kingdom (5.4%), France (5.2%), Turkey (3.2%), Norway (3%), India (2.8%), Sweden (2.7%), Germany (2.6%) and Switzerland (2.4%). These 12 countries, out of 233, contributed 71.4% of the scientific production on hydropower, which means that this research is highly concentrated, as was the case with solar and wind energy.

Large-scale hydro technology is one of the more mature technologies [52]; therefore, there is no increase in rates of research, as shown in Fig. 2. Scientific publications research is focused on studying the potential of small hydropower in countries with potential in this resource, such as Spain [61], Turkey [62,63], India [64], Kenya [65], Nigeria [66], Thailand [67] and Nepal [68]. Large hydro will increase from 266 Mtoe (million tons

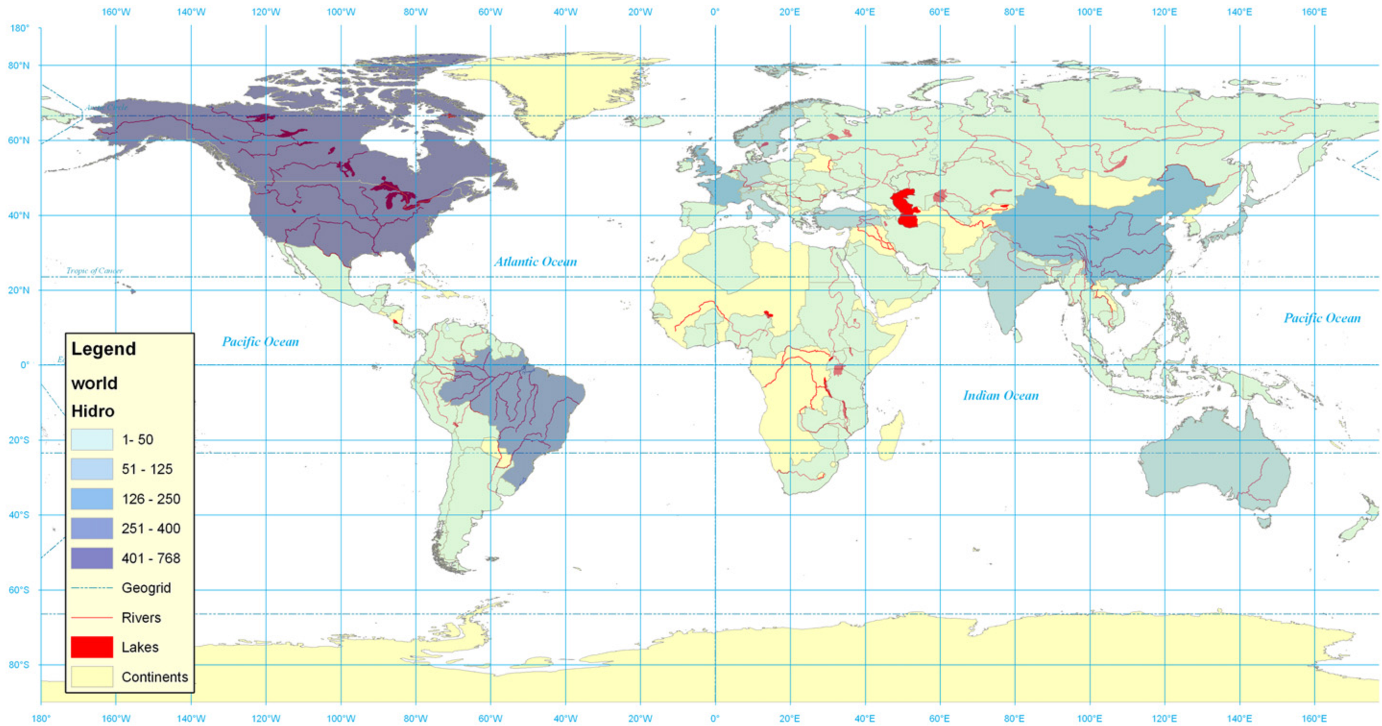


Fig. 5. World map of the number of scientific journals published on hydropower in the period 1979–2009.

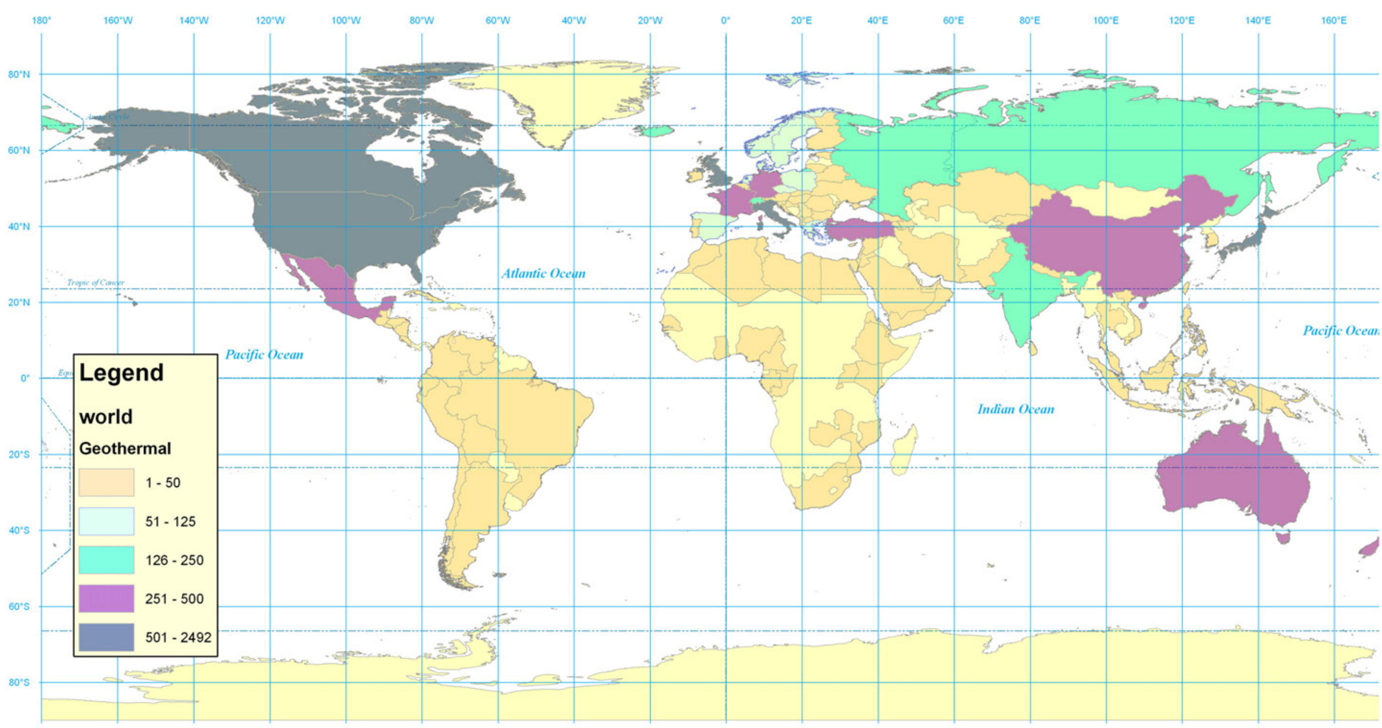


Fig. 6. World map of the number of scientific journals published on geothermal energy in the period 1979–2009.

oil equivalent) in 2010 to 358 in 2040, while small hydro will increase from 19 to 189 Mtoe in the same period [19,50].

3.2.4. Geothermal

Geothermal energy is the energy contained as heat inside the Earth. Geothermal energy for electricity generation has been produced commercially since 1913 [69]. Geothermal electricity and heat are limited to the characteristics of local resources and reservoirs. The substantial potential of geothermal energy is limited to certain parts of the world, whereas the potential for small-scale applications (heat pumps) is broader. Technical exploitable potential will increase during the next several years due to innovation, whereas the limitations of the potential will lead to a steady reduction of growth rates [50]. Electricity is produced with an efficiency of 10–17% [51], and the geothermal

kW h production is generally cost-competitive with conventional sources of energy. This source has also other uses, the thermal capacity in non-electrical uses are usually greenhouses, aquaculture, district heating or industrial processes [70].

Fig. 6 shows the number of scientific publications in the period 1979–2009 in all countries on geothermal energy. The following countries have contributed the most scientific publications in this field: USA(25.5%), Japan (6.14%), Italy (6%), United Kingdom (5.6%), Canada (5.3%), France (5%), New Zealand (4.9%), Germany (3.9%), China (3.9%), Turkey (3.3%), Australia (3%), Mexico (2.8%), Russia (2.4%) and Iceland (2.1%). These 14 countries, out of 233, contributed 80.4% of the scientific production on geothermal energy, which means that this research is highly concentrated, as in the case of all renewable energies previously studied.

It is expected that geothermal energy production will increase from 86 Mtoe (million tons oil equivalent) in 2010 to 493 Mtoe by the year 2040 [19], thus accounting for 4% of the renewable energy in the world for that year [50].

3.2.5. Biomass

Biomass represents an abundant carbon-neutral renewable resource for the production of bio-energy and biomaterials, and its enhanced use would address several societal needs [71]. At present, forestry, agricultural and municipal residues, and wastes are the main feedstocks for the generation of electricity and heat from biomass. In addition, very small shares of sugar, grain and vegetable oil crops are used as feedstocks for the production of liquid biofuels. Today, biomass supplies approximately 50 EJ globally, which represents approximately 10% of the global annual primary energy consumption. This is mostly traditional biomass that is used for cooking and heating [60].

Of the total bio-energy produced today, wood biomass accounts for 87%, agricultural crops for 9% and municipal and industrial waste for 4% [60]. Biomass will increase from 1313 Mtoe (million tons oil equivalent) in 2010 to 3271 Mtoe in 2040 [50]. Currently, the global yield for all biomass crops, including woody and herbaceous crops growing in temperate and subtropical regions, varies from 8 dry t ha^{-1} $year^{-1}$ (for willow in Sweden) to 10 to 22 dry t ha^{-1} $year^{-1}$ (for short-rotation woody crops in the USA). Some commercial plantations in Brazil have reported up to 20 dry t ha^{-1} $year^{-1}$. A conservative global biomass average would be 10 dry t ha^{-1} $year^{-1}$, although some small-scale field trials have reported four times this level of biomass production [72,73]. This production of biomass, also achieved in some greenhouse crops in southern Spain, such as tomato, is 9.8 dry t ha^{-1} $year^{-1}$ [74–76].

Fig. 7 shows the number of scientific publications on biomass in the period 1979–2009 in all countries. The following countries have contributed the most scientific publications in this field:

Table 1
Leading global scientific institutions by number of scientific journals published on solar energy in the period 1979–2009.

Institution	Solar (%)
NASA	3.72
CHINESE ACAD SCI	2.20
RUSSIAN ACAD SCI	1.92
UNIV CALIF BERKELEY	1.59
CALTECH	1.54
UNIV MARYLAND	1.17
NATL RENEWABLE ENERGY LAB	1.10
INDIAN INST TECHNOL	1.04
UNIV COLORADO	1.03
OSAKA UNIV	1.01
UNIV TOKYO	1.00
CNRS	0.95
UNIV CALIF LOS ANGELES	0.91
JOHNS HOPKINS UNIV	0.88
KYOTO UNIV	0.83
OBSERV PARIS	0.80
UNIV LONDON IMPERIAL COLL SCI TECHNOL & MED	0.78
UNIV NEW HAMPSHIRE	0.75
NATL CTR ATMOSPHER RES	0.74
Univ Arizona	0.73

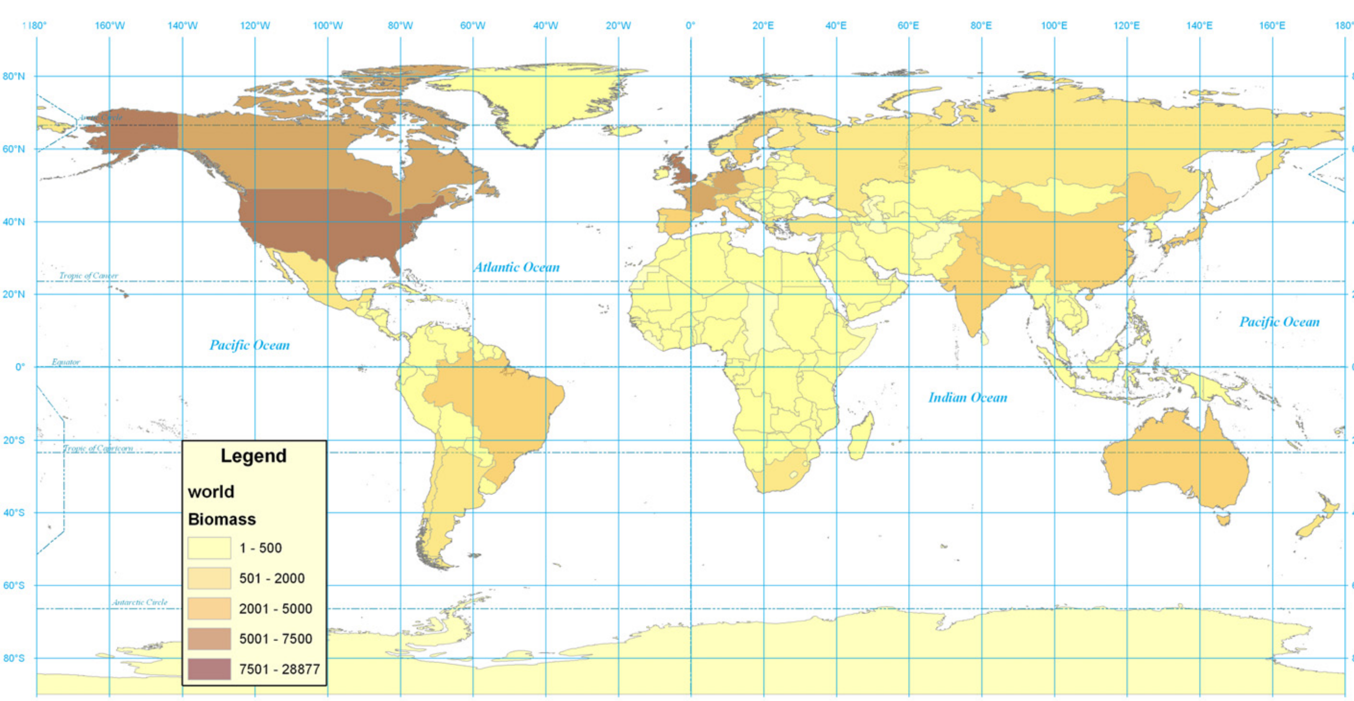


Fig. 7. World map of the number of scientific journals published on biomass in the period 1979–2009.

USA(23.1%), United Kingdom (6.2%), Canada (5.4%), Germany (5.3%), France (4.2%), China (3.9%), Spain (3.7%), Australia (3.5%), India (3.4%), Japan (3%), Netherlands (2.9%), Sweden (2.5%), Italy (2.4%) and Brazil (2.4%). These 14 countries, out of 233, contributed 72.1% of the scientific production on geothermal energy, which means that this research is highly concentrated, as in the case of all renewable energies previously studied.

Plenty of research on the efficiency and sustainability of biomass energy has focused on Europe, North America and a few emerging economies, such as Brazil, China, Russia, Indonesia and India, which is at least partially attributable to their large and/or rapidly growing energy demands, their resources in fossil fuels (e.g., oil and gas in Russia, coal in China) and/or alternative fuel sources (e.g., sugar cane for bioethanol in Brazil and palm oil for biodiesel in Indonesia) [77].

It is noticeable the strong research conducted by southern European countries such as Spain, France and Italy, which apparently do not have large biomass resources and are, therefore, trying to use agricultural resources, industrial products or residues of urban areas. The state of gasification technology is still in development, while co-fired and direct-fired biomass are in a state of deployment [19].

3.3. *World's leading scientific institutions for research on renewable energy*

This section presents the main scientific institutions in the world that have most contributed to scientific progress in various fields of renewable energy. We have considered the 20 institutions that have provided the most scientific production in the last 30 years (see Tables 1–5). The following sections are studied for each of the renewable energies.

Table 2
Leading global scientific institutions by number of scientific journals published on wind energy in the period 1979–2009.

Institution	Wind (%)
NASA	4.69
UNIV CALIF BERKELEY	1.97
RUSSIAN ACAD SCI	1.94
JOHNS HOPKINS UNIV	1.77
UNIV MARYLAND	1.72
UNIV COLORADO	1.72
CALTECH	1.69
NOAA	1.58
UNIV CALIF LOS ANGELES	1.43
NATL CTR ATMOSPHER RES	1.37
CHINESE ACAD SCI	1.35
UNIV WASHINGTON	1.22
MIT	1.19
UNIV NEW HAMPSHIRE	1.06
KYOTO UNIV	1.03
UNIV TOKYO	1.00
MAX PLANCK INST AERON	0.99
HARVARD SMITHSONIAN CTR ASTROPHYS	0.96
LOS ALAMOS NATL LAB	0.96
UNIV MICHIGAN	0.93

Table 3
Leading global scientific institutions by number of scientific journals published on biomass in the period 1979–2009.

Institution	Biomass (%)
CHINESE ACAD SCI	1.58
USDA ARS	1.39
CSIC	1.10
RUSSIAN ACAD SCI	1.04
OREGON STATE UNIV	0.91
INRA	0.90
UNIV FLORIDA	0.90
SWEDISH UNIV AGR SCI	0.89
UNIV CALIF DAVIS	0.79
CSIRO	0.78
US FOREST SERV	0.77
NASA	0.71
UNIV WISCONSIN	0.70
UNIV GEORGIA	0.69
UNIV MINNESOTA	0.67
UNIV WASHINGTON	0.63
COLORADO STATE UNIV	0.62
UNIV MARYLAND	0.61
UNIV BRITISH COLUMBIA	0.59
NOAA	0.59

Table 4
Leading global scientific institutions by number of scientific journals published on hydropower in the period 1979–2009.

Institution	Hydropower (%)
CHINESE ACAD SCI	1.40
UNIV MANITOBA	1.34
UNIV QUEBEC	1.25
US GEOL SURVEY	1.16
FISHERIES & OCEANS CANADA	1.13
HYDRO QUEBEC	1.01
UNIV SAO PAULO	0.89
UNIV WASHINGTON	0.89
INDIAN INST TECHNOL	0.81
UNIV ALBERTA	0.81
KARADENIZ TECH UNIV	0.78
UNIV WATERLOO	0.72
COLORADO STATE UNIV	0.69
NOAA	0.69
NORWEGIAN UNIV SCI & TECHNOL	0.63
PACIFIC NW NATL LAB	0.63
UNIV OSLO	0.63
ASIAN INST TECHNOL	0.60
OAK RIDGE NATL LAB	0.60
UNIV BRITISH COLUMBIA	0.60

Table 5
Leading global scientific institutions by number of scientific journals published on geothermal energy in the period 1979–2009.

Institution	Geothermal (%)
US GEOL SURVEY	3.85
RUSSIAN ACAD SCI	2.09
CNR	2.00
UNIV AUCKLAND	1.86
UNIV ICELAND	1.58
CHINESE ACAD SCI	1.45
INST INVEST ELECT	1.33
UNIV UTAH	1.30
UNIV CALIF BERKELEY	1.21
BUR RECH GEOL & MINIERES	1.14
UNIV ALBERTA	1.12
STANFORD UNIV	1.11
INST GEOL & NUCL SCI	1.03
UNIV TOKYO	1.02
UNIV NACL AUTONOMA MEXICO	0.99
DSIR	0.97
TOHOKU UNIV	0.94
GEOL SURVEY JAPAN	0.92
GEOL SURVEY CANADA	0.88
UNIV SIENA	0.88

3.3.1. Solar energy

The institution that has the most publications on solar energy in the last 30 years is NASA, followed by the Chinese Academy of Sciences (CHINESE ACAD SCI) and, third, the Russian Academy of Sciences. Of the 20 most published institutions, 11 are from the USA, 3 are from Japan and 2 are from France.

3.3.2. Wind energy

With regard to solar energy, the institution that contributed the most to wind energy is NASA, followed by the University of California (Berkeley) and then by the Russian Academy of Sciences. The Chinese Academy of Sciences occupies the eleventh place. Of the 20 most published institutions, 15 are from the USA and 2 are from Japan.

3.3.3. Biomass

It is noted that the CHINESE ACAD SCI (China) is the institution with the most research efforts devoted to the study of biomass, followed by the USDA ARS (U.S.) and, third, the CSIC (Spain). If institutions are grouped by country, it is clear that the research efforts in the study of biomass are generally concentrated in one institution per country, except the USA, which has 12 of the 20 institutions that have generated more scientific production on biomass, with NASA foremost among them.

The other countries that have institutions with high scientific production in this field are France (INRA), Sweden (SWEDISH UNIV AGR SCI) and Australia (CSIRO). In this study, it is striking that there are institutions in countries such as Spain and France that devote much effort to the study of biomass. These studies may be on seasonal biomass from crops and industrial and urban waste, as they are not countries with large biomass resources compared with the others.

3.3.4. Hydropower

The institution that has the most publications on hydropower is the Chinese Academy of Sciences, followed by two institutions from Canada, namely, the University of Manitoba and the University of Quebec. Of the 20 most published institutions, 7 are from Canada, 5 are from the US, and 2 are from Norway.

3.3.5. Geothermal

The study of geothermal energy has been led by the U.S. Geological Survey, followed by the Russian Academy of Sciences and, third, by the CNR. Of the 20 most published institutions, 4 are in the USA, 3 each in New Zealand and Japan, 2 each in Canada, Mexico and Italy, and 1 each in Russia, Iceland, France and China.

4. Conclusion and outlook

Although being the most produced energy form, hydropower is not the most investigated RES, and its rate of publication has been stable over the past 30 years and represents 2% of the total renewable energy publications. This low percentage may be due to the fact of being a mature and fully exploited technology, with the bulk of research into this energy being devoted to small hydropower. Hydropower is studied by countries that have the most of this resource, including the USA, Canada, Brazil and China. The Chinese Academy of Sciences is the institution with the most publications, and of the 20 most published institutions, 7 are from Canada, 5 from the USA and 2 from Norway.

Geothermal energy is considered not yet mature. Nevertheless, it was associated with a publication rate similar to hydropower; however, perhaps because its substantial potential is limited to some parts of the world, countries that have contributed to this field are those that have this resource: USA, Japan, Italy, UK and Canada. The study of geothermal energy has been led by the U.S. Geological Survey. The 20 institutions that have published the most papers are relatively evenly distributed by country. The publications in this field account for 5% of the total renewable energy publications.

The publications on wind power account for 11% of the total renewable energy publications. Wind energy has been associated with an increasing rate of research, especially since 2005. This technology is considered to have matured with respect to onshore production, while with offshore production, it is at the beginning of a deployment phase. The countries that have contributed in this field are the USA, the United Kingdom, Germany, Japan and France. The institution that has contributed the most is NASA, followed by the University of California (Berkeley) and then the Russian Academy of Sciences. Note that of the 20 most published institutions, 15 are from the USA.

Solar energy has various associated technologies in various stages of maturity. A publication on solar energy clearly stands at a second position in the number of publications (26% of the total). Their publication rate is exponential, and the research on solar energy dates back to 1991. The countries that have the most contributions in this field are the USA, Japan, Germany, the United Kingdom and China. The research centre with the most publications in the world is NASA, followed by the Chinese Academy of Sciences and, third, the Russian Academy of Sciences. Of the 20 most published institutions, 11 are from the USA, 3 from Japan and 2 from France. It is noteworthy that there are large areas of the world with this resource that have no research on this energy.

The study of biomass occupies 56% of renewable energy research, and the publication rate is exponential and experienced a large increase from 1990 to 1991. The countries that have the most contributions in this field are the USA, the United Kingdom, Canada, Germany and France. The CHINESE ACAD SCI (China) is the institution with the greatest research effort devoted to the study of biomass, followed by the USDA ARS (U.S.) and, third, the CSIC (Spain). The latter institution is of particular note, as Spain is not rich in biomass resources. The USA has 12 of the 20 institutions that have generated the most scientific production on biomass, and NASA is one among them.

As a final conclusion, this work shows that renewable energy research is highly concentrated in a few countries, 12 or 14 depending upon the energy, accounting for 70 to 80% of the total scientific production. The USA is the leader in research in all renewable energy categories studied. NASA is the lead institution for solar and wind energy, the CHINESE ACAD SCI leads in hydropower and biomass, and the U.S. Geological Survey leads in geothermal energy.

References

[1] Hernandez-Escobedo Q, Manzano-Agugliaro F, Zapata-Sierra A. The wind power of Mexico. Renewable & Sustainable Energy Reviews 2010;14(9):2830–40.
[2] Tolón-Becerra A, Lastra-Bravo X, Bienvenido-Bárcena F. Proposal for territorial distribution of the EU 2020 political renewable energy goal. Renewable Energy 2011;36(8):2067–77.
[3] Manzano-Agugliaro F, Carrillo-Valle J. Location of air in-leakage in power plants condensers by helium test. DYNA 2011;86(2):173–81.
[4] Demirbas A. Energy issues and energy priorities. Energy Sources, Part B: Economics, Planning and Policy 2008;3(1):41–9.
[5] Demirbas A. Recent advances in biomass conversion technologies. Energy Education Science and Technology 2000;6:19–40.
[6] Vinichuk M, Rosén K, Johanson KJ, Dahlberg A. Correlations between potassium, rubidium and cesium (133Cs and 137Cs) in sporocarps of Suillus variegatus in a Swedish boreal forest. Journal of Environmental Radioactivity 2011;102(4):386–92.
[7] Galván I, Mousseau TA, Møller AP. Bird population declines due to radiation exposure at Chernobyl are stronger in species with pheomelanin-based coloration. Oecologia 2011;165(4):827–35.

[8] Kuchma O, Finkeldey R. Evidence for selection in response to radiation exposure: pinus sylvestris in the Chernobyl exclusion zone. Environmental Pollution 2011;159(6):1606–12.
[9] Cardis E, Hatch M. The Chernobyl accident—an epidemiological perspective. Clinical Oncology 2011;23(4):251–60.
[10] Gluzman SF. The Chernobyl accident—a personal perspective. Clinical Oncology 2011;23(4):306–7.
[11] Cruz-Peragon F, Palomar JM, Casanova PJ, Dorado MP, Manzano-Agugliaro F. Characterization of solar flat plate collectors. Renewable and Sustainable Energy Reviews 2012;16(3):1709–20.
[12] Manzano-Agugliaro F, Hernandez-Escobedo Q, Zapata-Sierra A. Use of bovine manure for ex situ bioremediation of diesel contaminated soils in Mexico. Itea-informacion Tecnica Economica Agraria 2010;106(3):197–207.
[13] Manzano-Agugliaro F, Sanchez-Muros MJ, Barroso FG, Martínez-Sánchez A, Rojo S, Pérez-Bañón C. Insects for biodiesel production. Renewable and Sustainable Energy Reviews 2012;16(6):3744–53.
[14] Kalogirou SA. Solar thermal collectors and applications. Progress in Energy and Combustion Science 2004;30(3):231–95.
[15] Hernandez-Escobedo Q, Manzano-Agugliaro F, Gazquez-Parra JA, Zapata-Sierra A. Is the wind a periodical phenomenon? The case of Mexico Renewable & Sustainable Energy Reviews 2010;15(1):721–8.
[16] Baños R, Manzano-Agugliaro F, Montoya FG, Gil C, Alcayde A, Gómez J. Optimization methods applied to renewable and sustainable energy: a review. Renewable and Sustainable Energy Reviews 2011;15(4):1753–66.
[17] Charters WWS. Developing markets for renewable energy technologies. Renewable Energy 2001;22:217–22.
[18] Dincer I. Environmental impacts of energy. Energy Policy 1999;27:845–54.
[19] Panwar NL, Kaushik SC, Kothari S. Role of renewable energy sources in environmental protection a review. Renewable and Sustainable Energy Reviews 2011;15(3):1513–24.
[20] Jagoda K, Lonseth R, Lonseth A, Jackman T. Development and commercialization of renewable energy technologies in Canada: an innovation system perspective. Renew Energy 2011;36:1266–71.
[21] Lund PD. Effects of energy policies on industry expansion in renewable energy. Renewable Energy 2009;34:53–64.
[22] Cansino JM, Pablo-Romero MP, Román R, Iñiguez R. Tax incentives to promote green electricity: an overview of EU-27 countries. Energy Policy 2010;38:6000–8.
[23] Sims R, Rogner HH, Gregory K. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. Energy Policy 2003;31:1315–26.
[24] Dijkman TJ, Benders RMJ. Comparison of renewable fuels based on their land use using energy densities. Renewable & Sustainable Energy Reviews 2010;14(9): 3148–55.
[25] Fridleifsson IB. Geothermal energy for the benefit of the people. Renewable and Sustainable Energy Reviews 2001;5(3):299–312.
[26] UNDP. World Energy Assessment 2000—Energy and the Challenge of Sustainability. New York: UNDP; 2000 (ISBN 9211261260).
[27] Demirbas A. Global renewable energy projections. Energy Sources, Part B: Economics, Planning and Policy 2011;4(2):212–22.
[28] Kajikawa Y, Yoshikawa J, Takeda Y, Matsushima K. Tracking emerging technologies in energy research: toward a roadmap for sustainable energy. Technological Forecasting and Social Change 2008;75:771–82.
[29] Thomas SM. The evaluation of plant biomass research: a case study of the problems inherent in bibliometric indicators. Scientometrics 1992;23(1): 149–67.
[30] Uzun A. National patterns of research output and priorities in renewable energy. Energy Policy 2002;30:131–6.
[31] Hassan E. The evolution of the knowledge structure of fuel cells. Scientometrics 2005;62(2):223–38.
[32] Tsay M. A bibliometric analysis of hydrogen energy literature, 1965–2005. Scientometrics 2008;75(3):421–38.
[33] Kajikawa Y, Takeda Y. Structure of research on biomass and bio-fuels: a citation-based approach. Technological Forecasting and Social Change 2008;75(9):1349–59.
[34] Celiktas MS, Sevgili T, Tocar G. A snapshot of renewable energy research in Turkey. Renewable Energy 2009;34:1479–786.
[35] Romo-Fernández LM, López-Pujalte C, Guerrero Bote VP, Moya-Anegón F. Analysis of Europe's scientific production on renewable energies. Renewable Energy 2011;36(9):2529–37.
[36] Romo-Fernández, LM, Guerrero-Bote VP, Moya-Anegón, F World scientific production on renewable energy, sustainability and the environment. Energy for Sustainable Development2012. In press. Doi http://dx.doi.org/10.1016/j.esd.2012.06.005.
[37] Rojas-Sola JI, Jordá-Albiñana B. Bibliometric analysis of Mexican scientific production in hydraulic engineering based on journals in the Science Citation Index-Expanded database (1997–2008). Tecnologia y Ciencias del Agua. 2011;2(4):195–213.
[38] Rojas-Sola JI, de San-Antonio-Gómez C. Bibliometric analysis of spanish scientific publications in the subject construction and building technology in web of science database (1997–2008). Materiales de Construccion 2010;60(300):143–9.
[39] Rojas-Sola JI, de San-Antonio-Gómez C. Bibliometric analysis of Mexican scientific publications in the category engineering, chemical from the web of science data base (1997–2008). Revista Mexicana de Ingeniera Quimica 2010;9(3):231–40.
[40] Rojas-Sola JI, Antonio-Gómez CS. Bybliometric analysis of argentinean scientific publications in the agriculture, multidisciplinary subject category in web of science database (1997–2009). Revista de la Facultad de Ciencias Agrarias 2010;42(2):71–83.
[41] Rojas-Sola JI, San Antonio-Gómez C. Bibliometric analysis of Spanish scientific publications in the subject Metallurgy & Metallurgical Engineering in Web of Science database (1997–2008). Revista de Metalurgia (Madrid) 2010;46(6):555–62.
[42] Rojas-Sola JI, de San-Antonio-Gómez C. Bibliometric analysis of colombian scientific publications in Engineering, multidisciplinary subject category in web of science database (1997-2009). DYNA 2010;77(164):9–17.
[43] Rojas-Sola JI, Jordá-Albiñana B. Bibliometric analysis of Venezuelan scientific publications in the ecology category of the web of science database (1997–2008). Interciencia 2010;35(8):619–23.
[44] Rojas-Sola JI, Jordá-Albiñana B, Criado-Herrero E. Bibliometric analysis of Latin American, Spanish and Portuguese Scientific Publications in the subject materials science, ceramics in JCR (SCI) database (1997–2008). Boletin de la Sociedad Espanola de Ceramica y Vidrio 2009;48(6):297–310.
[45] Rojas-Sola JI, Jordá-Albiñana B. Bibliometric analysis of venezuelan publications in the computer sciences category of the JCR data base (1997–2007). Interciencia 2009;34(10):689–95.
[46] Rojas-Sola JI, Jordá-Albiñana B. Bibliometric analysis of Spanish Scientific Publications in the subject materials science, ceramics in JCR (SCI) database (1997–2008). Boletin de la Sociedad Espanola de Ceramica y Vidrio 2009;48(5):255–60.
[47] Rojas-Sola JI, Navarrete-Cortés J, Fernández-López JA, Chaichio-Moreno JA. Scientific production in the graphic expression in engineering area at the Spanish universities: an approach to ISI database. Revista Espanola de Documentacion Cientifica 2008;31(2):190–204.
[48] IEA (International Energy Agency). 2011. Clean energy Progress Report. 〈http://www.iea.org/papers/2011/CEM_Progress_Report.pdf〉.
[49] Glasnovic Z, Margeta J. Vision of total renewable electricity scenario. Renewable and Sustainable Energy Reviews 2011;15(4):1873–84.
[50] EREC, European Renewable Energy Council. 2006. Renewable energy scenario to 2040, half of the global energy supply from renewables in 2040, 〈http://www.censolar.es/erec2040.pdf〉.
[51] IEA (International Energy Agency). 2010. Key world energy statistics, 〈http://www.iea.org/textbase/nppdf/free/2010/key_stats_2010.pdf〉.
[52] EPRI (Electric Power Research Institute) 2010. Australian Electricity Generation Technology Costs—Reference Case 2010.
[53] Czisch G, 2001. Global Renewable Energy Potential. 〈http://www.iset.uni-kassel.de/abt/w3-w/folien/magdeb030901〉.
[54] Michalak P, Zimny J. Wind energy development in the world, Europe and Poland from 1995 to 2009; Current status and future perspectives. Renewable and Sustainable Energy Reviews 2011;15(5):2330–41.
[55] Gracia A, Barreiro-Hurlé J, Pérez y Pérez L. Can renewable energy be financed with higher electricity prices? Evidence from a Spanish region. Energy Policy 2012;50:784–94.
[56] Hernández-Escobedo Q, Manzano-Agugliaro F, Zapata-Sierra A. Wind strength description in the province of Almeria. DYNA 2009;84(8):681–6.
[57] Ruiz Romero S, Colmenar Santos A, Castro Gil MA. EU plans for renewable energy. An application to the Spanish case. Renewable Energy 2012;43: 322–30.
[58] Ruiz-Arias JA, Terrados J, Pérez-Higueras P, Pozo-Vázquez D, Almonacid G. Assessment of the renewable energies potential for intensive electricity production in the province of Jaén, southern Spain. Renewable and Sustainable Energy Reviews 2012;16(5):2994–3001.
[59] Míguez JL, López-González LM, Sala JM, Porteiro J, Granada E, Morán JC, et al. Review of compliance with EU-2010 targets on renewable energy in Galicia (Spain). Renewable and Sustainable Energy Reviews 2006;10(3):225–47.
[60] WEC (World Energy Council) 2010. 2010 Survey of energy resources executive summary. 〈http://www.worldenergy.org/documents/ser2010exsumsept8.pdf〉.
[61] Alonso-Tristán C, González-Peña D, Díez-Mediavilla M, Rodríguez-Amigo M, García-Calderón T. Small hydropower plants in Spain: a case study. Renewable and Sustainable Energy Reviews 2011;15(6):2729–35.
[62] Dursun B, Gokcol C. The role of hydroelectric power and contribution of small hydropower plants for sustainable development in Turkey. Renewable Energy 2011;36(4):1227–35.
[63] Uzlu E, Akpinar A, Kömürcü MT. Restructuring of Turkey's electricity market and the share of hydropower energy: the case of the Eastern Black Sea Basin. Renewable Energy 2011;36(2):676–88.
[64] Nautiyal H, Singal SK, Sharma Varun. A. Small hydropower for sustainable energy development in India. Renewable and Sustainable Energy Reviews 2011;15(4):2021–7.
[65] Kiplagat JK, Wang RZ, Li TX. Renewable energy in Kenya: resource potential and status of exploitation. Renewable and Sustainable Energy Reviews 2011;15(6):2960–73.
[66] Ohunakin OS, Ojolo SJ, Ajayi OO. Small hydropower (SHP) development in Nigeria: an assessment. Renewable and Sustainable Energy Reviews 2011;15(4):2006–13.
[67] Kosa P, Kulworawanichpong T, Srivoramas R, Chinkulkijniwat A, Horpibulsuk S, Teaumroong N. The potential micro-hydropower projects in Nakhon Ratchasima province, Thailand. Renewable Energy 2011;36(3):1133–4.
[68] Sovacool BK, Dhakal S, Gippner O, Bambawale MJ. Halting hydro: a review of the socio-technical barriers to hydroelectric power plants in Nepal. Energy 2011;36(5):3468–76.

[69] Fridleifsson IB. Geothermal energy for the benefit of the people. Renewable and Sustainable Energy Reviews 2001;5(3):299–312.
[70] Barbier E. Nature and technology of geothermal energy: a review. Renewable and Sustainable Energy Reviews 1997;1(1-2):1–69.
[71] Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA, et al. The path forward for biofuels and biomaterials. Science 2006;311(5760):484–9.
[72] Berndes G, Azar C, Kaberger T, Abrahamson D. The feasibility of large-scale lignocellulose-based bioenergy production. Biomass Bioenergy 2001;20(5): 371–81.
[73] Perlack, RD et al., Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. U.S. Department of Energy and U.S. Department of Agriculture, April 2005; available at 〈feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf〉.
[74] Agugliaro FM. Gasification of greenhouse residues for obtaning electrical energy in the south of spain: localization by gis. Interciencia 2007;32(2):131–6.
[75] Callejón-Ferre AJ, Velázquez-Martí B, López-Martínez JA, Manzano-Agugliaro F. Greenhouse crop residues: energy potential and models for the prediction of their higher heating value. Renewable and Sustainable Energy Reviews 2011;15(2):948–55.
[76] Callejón-Ferre AJ, Velázquez-Martí B, López-Martínez JA, Manzano-Agugliaro F. Erratum to: Greenhouse crop residues: energy potential and models for the prediction of their higher heating value [Renew. Sust. Energy Rev. 15 (2) (2011) 948-955] (http://dx.doi.org/10.1016/j.rser.2010.11.012). Renewable and Sustainable Energy Reviews 2011;15 (9):5224.
[77] Srebotnjak T, Hardi P. Prospects for sustainable bioenergy production in selected former communist countries. Ecological Indicators 2011;11(5): 1009–19.